Neutrino oscillations in core-collapse supernovae*

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Neutrinos play essential roles in determining the dynamics and nucleosynthesis of core-collapse supernova explosion since they carry away nearly all the gravitational binding energy released during the collapse. On the other hand, the detection of future Galactic supernova neutrinos could be exploited to explore the physics of core-collapse supernovae and properties of neutrinos. How neutrino oscillations among all three flavors of neutrinos and antineutrinos occur in supernova environment and how will oscillations affect different aspects mentioned above needs to be carefully examined.

We performed a comprehensive calculation of neutrino oscillations in supernovae, including the collective oscillations [1] that may happen due to the presence of large neutrino fluxes above the proto-neutron star and the Mikheyev-Smirnov-Wolfenstein (MSW) flavor transformation [2, 3]. In this study, we employed the neutrino emission characteristics and electron number density profiles calculated self-consistently in an 18 $M_\odot$ supernova model [4] and took into account the time evolution of these quantities over the neutrino emission timescale of ~ 10 seconds. We then examined the effect of neutrino oscillations on different nucleosynthesis processes and on the neutrino signals. [5]

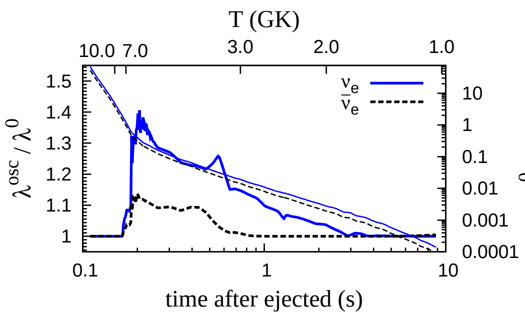

Figure 1: ν_e and $\bar{\nu}_e$ absorption rates $\lambda_{\rm osc}$, including oscillations and λ_0, without oscillations as a function of time.

Fig. 1 shows how collective neutrino oscillations change the ν_e ($\bar{\nu}_e$) absorption rates, λ, on neutrons (protons) for an example mass element ejected by neutrino-heating (the so-called ν-driven wind). Although the ν_e and $\bar{\nu}_e$ absorption rates are enhanced by $\sim 25\%$ and $\sim 10\%$ due to the flavor oscillations of $\nu_e \leftrightarrow \nu_{\mu,\tau}$ and $\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu,\tau}$ for some period of time, the enhancement occurs after the ^{4}He formation at the temperature $T \sim 7$ GK and before $T \gtrsim 3$ GK when νp process [6] operates such that the overall impact of oscillations on the ν-driven wind nucleosynthesis is negligible.

For the production of the rare isotopes ^{138}La and ^{180}Ta in the O/Ne shell of the star through ν_e absorption on ^{138}Ba and ^{180}Hf, the rates can be enhanced by up to $\sim 80\%$ and $\sim 60\%$ for those two interactions by collective neutrino oscillations and can potentially increase the production of ^{138}La and ^{180}Ta by $\sim 10\%$ when integrating over the neutrino emission time. Note that the above results assume the inverted neutrino mass hierarchy (IH) since in our model collective neutrino oscillations are suppressed in the normal neutrino mass hierarchy (NH).

For the neutrino-induced nucleosynthesis in the He shell, where the mass density $\rho \lesssim 10^3$ g/cm^3, the MSW flavor transformation has to be taken into account. In this supernova model, since the supernova shock only arrives the MSW resonance region at $\sim$ 5 s post bounce, the MSW flavor transformation can be treated adiabatically before that. We found that for the part of He shell located between $5.5 \times 10^4 \lesssim 4 \times 10^5$ km, the reaction $\nu_e + {}^4\text{He} \to {}^3\text{He} + p + e^-$ is enhanced by a factor of ~ 32 for the NH while $\bar{\nu}_e + {}^4\text{He} \to {}^3\text{H} + n + e^+$ is enhanced by ~ 17 for the IH, mainly due to the MSW transformation. This may affect the total production of light elements such as ^{7}Li and ^{11}B in supernovae.

Lastly, we looked at the effect of neutrino oscillations on the Galactic neutrino signals for different detection channels of neutrino flavors, e.g. the Super-Kamiokande detector for mainly $\bar{\nu}_e$ and a hypothetical liquid argon detector for mainly ν_e detection. We found that the time-integrated neutrino energy spectra detected during the first 0.5 s of the neutrino emission may be used to infer the neutrino mass hierarchy, when combined with the total detected event rates as a function of time.

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